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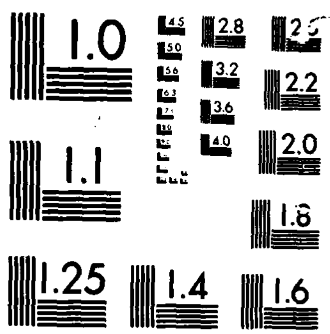

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Optoelectronic Devices and Related Physical Phenomena in Thin Film Semiconductor Configurations

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INTRODUCTION

The following report summarizes the main findings of the research program in "Optoelectronic Devices and Related Physical Phenomena in Thin Film Semiconductor Configurations." The main areas of research were:

1. Laser Arrays
2. Unstable Resonator Semiconductor Lasers
3. Novel Laser Structures and Laser Physics
4. Theory and Measurement of Noise in Semiconductor Lasers

These are described in detail in what follows.

1. LASER ARRAYS

Until recently, almost all semiconductor laser phased arrays have suffered from undesirable double lobed far-field patterns. During the past several years we have, therefore, undertaken a thorough theoretical and experimental study of phased arrays which culminated in the demonstration of several new array structures which achieve the desired single lobe far-field operation.

Most of the published works on the subject of semiconductor laser coherent power combining have reported various configurations of laser arrays on common substrates. The lasers are placed in close proximity to each other so there is sufficient interaction to assure their phase-locking. An important feature of such arrays is that a single contact is applied to all the lasers, i.e., they are internally connected electrically in parallel. This has important consequences regarding the operation of the array, since individual diode elements

cannot be accessed independently and thus there is no control over the internal functioning of the device. In response to this problem we have designed, fabricated and tested a novel type of 8-element phase-locked semiconductor laser array where each diode laser has its own separate contact[3] (Figure 1a), which provides an additional degree of freedom in the design of monolithic arrays which can be used for example, to compensate for device-to-device nonuniformities, tailor the near-field and far-field distributions and perform other functions.[4] This array also serves as a small-scale "laboratory" for investigating the basic physical processes governing the coupling interactions among the integrated lasers.

Experimental results include the demonstration of control over the near-field (Figure 1b),[2] the far-field[4,5] distributions of several elements of the array. A reduction in the number of longitudinal modes and single longitudinal mode operation has been achieved.[4] In addition, basic beam scanning has been demonstrated,[6] and coupling mechanisms were investigated and found to be different in gain-guided lasers as compared to the evanescent wave coupling typically assumed for real index-guided lasers.[7,8]

An eight element monolithic array of GaAlAs electroabsorption modulator has been demonstrated by reverse bias operation of the separate contact array.[7] This device may be useful for intensity modulation in high spatial resolution applications.

Uniform semiconductor laser arrays tend to oscillate in a superposition of their supermodes, thus leading to large beam divergence and spectral spread. We have shown that supermode discrimination in gain-guided arrays, in favor of the desired

fundamental supermode, is made possible by the near-field interference patterns which result from the complex optical fields of the gain-guided lasers.[10] We have also demonstrated a uniform array which utilizes diffraction effects to couple the lasers.[9]

The main impediment to fundamental mode operation uniform evanescently coupled arrays is the existence of strong absorption in the interchannel regions. This absorption favors the oscillation of the out-of-phase supermodes which best "avoid" these lossy regions.[15] We developed a new array structure based on a square wave transverse modulation of the effective index in which the gain is uniform across the transverse dimension, thus removing the incentive for higher supermode oscillation and again leading to single lobed far-field operation.[9]

We proposed nonuniform structures[11] of phase-locked diode lasers, which make it possible to discriminate efficiently against all the higher order array supermodes. In these chirped arrays, the envelopes of the various supermodes, including the highest order one, differ significantly from each other. Thus, by proper tailoring of the gain distribution across the array, one can select the fundamental supermode. We then demonstrated a single contact tailored gain chirped array[12] in which the gain profile across the array is made strongly asymmetric by varying the width of the contact stripes. The device exhibited single lobed operation close to the diffraction limit for a single supermode. Fabrication of this device is simple, and suited to large-scale processing techniques.

Finally, we have carried out a rate equation analysis of phase-locked semiconductor laser arrays.[13] It was found that for given

(laser) current densities, the photon density distribution in the array elements is that particular one which maximizes the total photon density. The results of this analysis were then combined with the waveguiding properties of the laser array waveguide, yielding a basic model of phase-locked diode laser arrays. This model explains the effects of the variation of the current combination through the array elements on its mode structure that were observed recently.

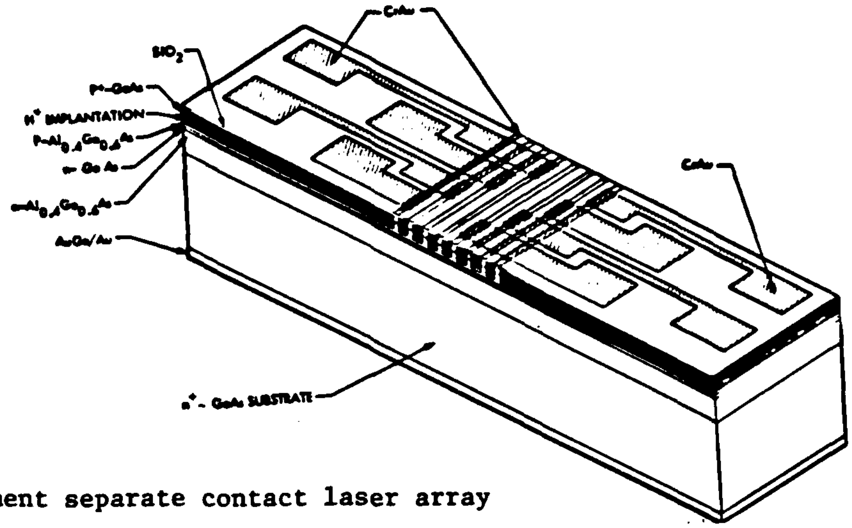

Fig. 1(a): 8 element separate contact laser array

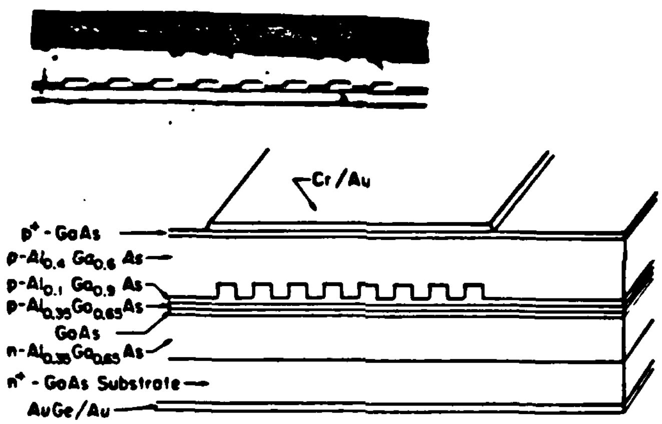

Fig. 1(b): Buried ridge phased array

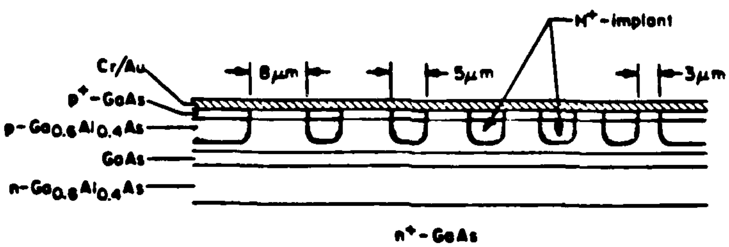

Fig. 1(c): Single contact tailored gain chirped array of proton implanted lasers.

2. UNSTABLE RESONATOR SEMICONDUCTOR LASERS

Laser cavities of the unstable resonator (UR) type have been shown to exhibit many advantages when combined with a lasing medium characterized by a high single-pass gain.[17-20] The most prominent of these advantages is the potential for increasing the mode volume of a laser oscillator while maintaining high descrimination between transverse modes. As a result, the cavity is relatively insensitive to inhomogeneities in the lasing medium. These properties make UR geometries very attractive for semiconductor lasers,[21] since they may provide an optimal solution to the task of increasing the lateral dimension of the laser and avoiding multi-lateral mode operation and filamentation.

In order to fabricate UR semiconductor lasers, a technique for etching curved facets into the GaAs/GaAlAs was developed by us.[22] As a first application, double heterostructure lasers were fabricated in which one of the laser facets was produced by a hybrid wet and reactive-ion-etching technique. This technique is suitable for GaAs/GaAlAs heterostructure lasers and utilizes the selectivity of Freon-12 plasma in preferentially etching GaAs over GaAlAs. Lasers fabricated by this technique are compatible with optoelectronic integration and have threshold currents and quantum efficiency comparable to lasers with both mirrors formed by cleaving. The technique enables the use of relatively higher pressures of noncorrosive gases in the etch plasma resulting in smoother mirror surfaces and further eliminates the nonreproducibility inherent in

the etching of GaAlAs layers. Then, GaAs heterostructure lasers with unstable resonator cavities were demonstrated for the first time with both curved mirrors fabricated by etching. Typical output powers of 0.35 Watts were observed in a stable, highly coherent lateral mode. The laser operated stably in a single longitudinal mode over a large range of injection currents. The external quantum efficiency was 70% that of a similar laser with both cleaved mirror facets implying good output coupling of the energy from the entire region.[23] In these lasers, single lateral mode operation was demonstrated by measuring the spatial degree of coherence of the laser output.[24] If the highly astigmatic beam is corrected by appropriate external optics, the focusing capability of these lasers may lead to power densities in a single mode higher than that emitted by any other semiconductor sources reported until now.[24]

In order to reduce the cavity losses in UR lasers, an unstable resonator semiconductor laser with a real index lateral waveguide has been also fabricated. Output powers in excess of 400 mW were observed with a stable, highly coherent lateral field distribution. The incorporation of a lateral real index waveguide with the unstable resonator configuration results in a substantial increase in the external quantum efficiency and a decrease in the threshold current of the UR laser.[25]

The successful fabrication of semiconductor lasers with curved mirrors indicates that laser cavities of different geometries can be designed as well and the cavity design can be tailored to specific needs in the output beam characteristics. As examples of other cavity design, and eventual applications, we demonstrated a

tilted mirror semiconductor laser,[26] a confocal unstable resonator semiconductor laser,[27] and an array of phase locked unstable resonator lasers.[28]

3. NOVEL LASER STRUCTURES AND LASER PHYSICS

A variety of new lasers have been demonstrated in GaInAs/InP. Low Threshold InGaAsP/InP injection lasers on semi-insulating InP substrates have been developed with mirrors fabricated by the microcleavage technique. Miniature suspended bridges containing the laser channels have been formed and then microcleavage has been accomplished by the use of ultrasonic vibrations. Lasers with current thresholds as low as 18 mA with 140μm cavity length and 35-45% differential quantum efficiency have been obtained.[29]

Mode stabilized terrace-large optical cavity (TR-LOC) lasers have been fabricated on semi-insulating (SI) InP substrates. The fabrication process involves a single-step liquid phase epitaxial (LPE) growth and a lateral Zn diffusion. The laser operates in a stable single transverse mode and is capable of delivering a power exceeding 300 mW/facet (at pulsed operation) with very smooth far-field pattern.[30]

Inverted strip buried heterostructure lasers have been fabricated. These lasers have threshold currents and quantum efficiencies that are comparable to those of conventional buried heterostructure lasers. The optical mode is confined by a weakly guiding strip loaded waveguide which makes possible operation in the fundamental transverse mode for larger stripe widths than is possible for conventional buried heterostructure lasers. Scattering of the laser light by irregularities in the sidewalls of the waveguide, which can be a serious problem in conventional buried heterostructure lasers, is also greatly reduced in these lasers.[32]

Very low threshold InGaAsP terrace lasers on semi-insulating (SI) InP substrate have been fabricated using the mass transport technique. The fabrication process involves a single-step liquid phase epitaxial (LPE) growth followed by a mass transport of InP at ~675°C in the presence of an InP cover wafer. Lasers operating in the fundamental transverse mode with smooth far-field patterns and threshold currents as low as 9.5 mA have been obtained.[33]

Short cavity length (38μm) lasers have been fabricated in GaInAsP/InP using a recently developed microcleavage technique. SiO_2-amorphous Si multilayer coatings have been evaporated on the lasers to obtain high reflectivity mirrors. The lasers have current thresholds as low as 3.8 mA with 85% reflecting front mirror and high reflectivity rear mirror and 2.9 mA with two high reflectivity mirrors. Single longitudinal mode operation is observed over a wide range of driving currents and temperatures.[34]

An undercut mesa laser is fabricated on an n^+-InP substrate using a single step liquid phase epitaxy growth process and a planar structure is obtained by using a polyimide filling layer. The lasers operate at fundamental transverse mode due to a scattering loss mechanism. Threshold currents of 18 mA and stable single transverse mode operating at high currents are obtained.[35]

The effects of the doping level in the P-cladding layer on the T_0 as high as 90 K has been observed. A new laser structure which involves a simple modification scheme applicable to most laser structures with improved temperature sensitivity has been demonstrated.[36]

Carrier leakage over the heterobarrier in an InGaAsP/InP laser is measured directly in a laser-bipolar-transistor structure. Experimental results indicate a significant amount of carrier leakage under normal laser operating conditions.[37]

The interband Auger recombination lifetimes of two Auger processes have been calculated to correlate measured threshold current densities and carrier lifetimes for InGaAsP and InGaAsSb lasers. Good agreement with experimental data was obtained for lasers with low nominal threshold current densities. These results demonstrate the importance of Auger recombination in the threshold characteristics of InGaAsP/InP lasers.

4. THEORY AND MEASUREMENT OF NOISE IN SEMICONDUCTOR LASERS:

In this work we have explained theoretically and accounted for experimentally a variety of basic stochastic properties of the electric field emitted from a semiconductor laser. In particular, properties related to the spectral purity of this field. This work is important to a number of potential applications of these devices which are now under intensive study. This includes coherent systems and certain sensing applications such as the fiber ring gyro. These applications require sources which exhibit extremely good frequency stability as gauged by their field spectrum linewidth.

Until very recently it was believed that the spectral purity of a single mode semiconductor laser was governed by physics similar to that found in other lasers. A few years ago it was believed that the fundamental linewidth of these devices was given by an equation known as the modified Schawlow-Townes linewidth formula. It was not until measurements were performed by Aram Mooradian's group at Lincoln Laboratories that this belief came under question.[39] They performed the first careful measurements of fundamental linewidth in a semiconductor laser. Their results indicated broadening some 20 to 40 times larger than predicted by the Schawlow-Townes formula (e.g., measured linewidths of 100 MHz at 1 milliwatt of output power versus a predicted 3 MHz at 1 milliwatt). Our initial interest in this field was sparked by these results.

Our ensuing work and that of others showed that, in fact, the linewidth in these devices was governed by an equation of the form [40-42]

$$\Delta\omega = \Delta\omega_{ST}(1 + \alpha^2)$$

Where $\Delta\omega_{ST}$ is the Schawlow-Townes linewidth and α is referred to as the linewidth enhancement factor. α is given by,

$$\alpha = \frac{\partial\chi_r/\partial n}{\partial\chi_i/\partial n}$$

where χ_r and χ_i are the real and imaginary components of the complex susceptibility function and n is a parameter describing the overall excitation level of the active medium, for instance, the carrier density. α results from the fact that semiconductor lasers, as a subset of the class of all regenerative oscillators, operate in a detuned mode. The result is that amplitude and phase fluctuations of the field are coupled together. This, in turn, allows components of quantum noise which will normally only influence the intensity noise of the device to now have a channel in the phase. This channeling of these fluctuations causes a degradation of lasing field spectral purity.

The value of α lies in the range -4 to -6 as inferred from linewidth versus power measurements conducted by our group and others. We have also calculated α from first principles for bulk material, finding values which also fall within this range.[43] In addition, we were able to establish a relation between this phase noise enhancement and the presence of chirping in the output of directly modulated semiconductor lasers. Our theory showed that besides enhancing the field spectrum linewidth of a semiconductor laser, the parameter α

also controls the apportioning of modulation energy into FM and AM components. We then used this formalism to achieve an independent measurement of the α parameter by measuring the ratio of FM to AM in several devices under direct current modulation.[44] The results gave α values which were in close agreement with values inferred from linewidth measurements.

References:

1. E. Kapon, J. Katz, S. Margalit, A. Yariv, "Longitudinal Mode Control in Integrated Semiconductor Laser Phase-Arrays by Phase Velocity Matching," Appl. Phys. Lett. 44, (1984).
2. E. Kapon, J. Katz, C. Lindsey, S. Margalit, A. Yariv, "Control of Mutual Phase Locking of Monolithically Integrated Semiconductor Lasers," Appl. Phys. Lett., 43, p. 421 (1983).
3. J. Katz, E. Kapon, C. Lindsey, S. Margalit, U. Shreter, A. Yariv, "Phase Locked Semiconductor Laser Array with Separate Contacts, Appl. Phys. Lett., 43, p. 521 (1983).
4. J. Katz, E. Kapon, S. Margalit, A. Yariv, "Recent Developments in Monolithic Phase-locked Semiconductor Laser Arrays," S.P.I.E., vol. 465 Spatial Light Modulators and Applications (1984).
5. J. Katz, E. Kapon, C. Lindsey, S. Margalit, A. Yariv, "Far-Field Distributions of Semiconductor Phase-Locked Arrays with Multiple Contacts," Electron. Lett., 19, p. 660 (1983).
6. E. Kapon, J. Katz, S. Margalit, A. Yariv, "Longitudinal Mode Control in Integrated Semiconductor Laser Phase-Arrays by Phase Velocity Matching," Appl. Phys. Lett., 44, (1984).
7. D. L. Robinson, W. K. Marshall, J. Katz, J. S. Smith, and A. Yariv, "Monolithically Integrated Array of GaAlAs Electroabsorption Modulators," Electron. Lett., 20, 17, 678 (1984).
8. J. Katz, S. Margalit, A. Yariv, "Diffraction Coupled Phase-Locked Semiconductor Laser Array," Appl. Phys. Lett., 42, 7, 554 (1983).
9. S. Mukai, C. Lindsey, J. Katz, E. Kapon, Z. Rav-Noy, S. Margalit

and A. Yariv, "Fundamental Mode Oscillation of a Buried Ridge Waveguide Laser Array," Appl. Phys. Lett., 45, 8, 834 (1984).

10. E. Kapon, C. Lindsey, J. Katz, S. Margalit, A. Yariv, "Coupling Mechanism of Gain-Guided Integrated Semiconductor Laser Arrays," Appl. Phys. Lett. 44, 389 (1984).

11. E. Kapon, C. Lindsey, J. Katz, S. Margalit and A. Yariv, "Chirped Arrays of Diode Lasers for Supermode Control," Appl. Phys. Lett. 45, 3, 200 (1984).

12. C. P. Lindsey, E. Kapon, J. Katz, S. Margalit and A. Yariv, "Single Contact Tailored Gain Phased Array of Semiconductor Lasers," Appl. Phys. Lett., 45, 7, 722 (1984).

13. J. Katz, E. Kapon, S. Margalit, A. Yariv, "Rate Equations Analysis of Phase-Locked Semiconductor Laser Arrays Under Steady State Conditions," IEEE J. Quantum Electron., QE-20, 8, 875 (1984).

14. E. Kapon, J. Katz, and A. Yariv, "Supermode Analysis of Phase-Locked Arrays of Semiconductor Lasers," Opt. Lett. 10, 125 (1984).

15. T. P. Lee, C. A. Burrus, B. I. Miller and R. A. Logan, IEEE J. Quantum Electron. QE-11, 432 (1975).

16. K. Aiki, M. Nakamura, J. Umeda, A. Yariv, A. Katzir and W. Yen, "GaAs-GaAlAs Distributed-feedback Diode Lasers with Separate Optical Carrier Confinement," Appl. Phys. Lett. 27, 145 (1975).

17. A. E. Siegman, Proc. IEEE 53, 277 (1965).

18. W. F. Krupke and W. R. Sooy, IEEE J. Quant. Electron. QE-5 575 (1969).

20. R. A. Chodzko, H. Mirels, F. S. Roehrs and R. Pedersen, IEEE J. Quant. Electron. QE-9, 523 (1973).

21. A. P. Bogatov, P. G. Eliseev, M. A. Man'ko, G. T. Mikaelyan and Y. M. Popov, Sov. J. Quant. Electron. 10 620 (1980).

22. J. Salzman, T. Venkatesan, S. Margalit and A. Yariv, "Double Heterostructure Lasers with Facets Formed by a Hybrid Wet and Reactive-Ion Etching Technique," J. Appl. Phys. 57, 2948 (1985).

23. J. Salzman, T. Venkatesan, R. Lang, M. Mittelstein and A. Yariv, "Unstable Resonator Cavity Semiconductor Lasers," Appl. Phys. Lett. 46, 218 (1985).

24. M. Mittelstein, J. Salzman, T. Venkatesan, R. Lang and A. Yariv, "Coherence and Focusing Properties of Unstable Resonator Semiconductor Lasers," Appl. Phys. Lett. 46, 923 (1985).

25. J. Salzman, R. Lang, T. Venkatesan, M. Mittelstein and A. Yariv, "Modal Properties of Unstable Resonator Semiconductor Lasers with a Lateral Waveguide," Appl. Phys. Lett. 47, 445 (1985).

26. J. Salzman, R. Lang, S. Margalit and A. Yariv, "Tilted-Mirror Semiconductor Lasers," Appl. Lett. 47, 9 (1985).

27. J. Salzman, R. Lang, M. Mittelstein and A. Yariv, paper presented at "Conference on Lasers and Electro Optics (Baltimore, 21-24 May, 1985).

28. J. Salzman and A. Yariv, to be presented at the Topical Meeting on Integrated and Guided Wave Optics," (Atlanta, 26-28 February 1986).

29. U. Koren, A. Hasson, K. L. Yu, T. R. Chen, S. Margalit and A. Yariv, "Low Threshold InGaAsP/InP Lasers with Microcleaved Mirrors Suitable for Monolithic Integration," Applied Physics Letters, 41, 9, pp. 791-793 (November 1982).

30. T. R. Chen, K. L. Yu, U. Koren, S. Margalit and A. Yariv, "Mode Stabilized InGaAsP/InP Terrace-Large Optical Cavity Laser Fabricated on Semi-Insulating InP," Japanese Journal of Applied Physics, 21, 9, pp. L595-L596 (September 1982).

31. H. Blauvelt, S. Margalit and A. Yariv, "AlGaAs Inverted Strip Buried Heterostructure Lasers," Applied Physics Letters, 41, 5, pp. 485-487 (September 1982).

32. T. R. Chen, L. C. Chiu, K. L. Yu, U. Koren, A. Hasson, S. Margalit, A. Yariv, "Low Threshold InGaAsP Terrace Mass Transport Laser on Semi-Insulating Substrate," Applied Physics Letters, 41, (12) pp. 1115-1117 (December 1982).

33. U. Koren, Z. Rav-Noy, A. Hasson, T. R. Chen, K. L. Yu, L. C. Chiu, S. Margalit and A. Yariv, "Short Cavity InGaAsP/InP Lasers with Dielectric Mirrors," Applied Physics Letters, 42, 10, pp. 848-850 (May 1983).

34. U. Koren, T. R. Chen, C. Harder, A. Hasson, K. L. Yu, L. C. Chiu, S. Margalit and A. Yariv, "InGaAsP/InP Undercut Mesa Laser with Planar Polyimide Passivation," Applied Physics Letters, 42, 5, pp. 403-405 (March 1983).

35. T. R. Chen, L. C. Chiu, K. L. Yu, U. Koren, A. Hasson, S. Margalit, and A. Yariv, "Dependence of T_0 on P-cladding Layer Doping Level in InGaAsP lasers," Japanese Journal of Applied Physics, 22, 9, pp. L559-L561 (September 1983).

36. T. R. Chen, B. Chang, L. C. Chiu, K. L. Yu, S. Margalit and A. Yariv, "Carrier Leakage and Temperature Dependence of InGaAsP Lasers," Applied Physics Letters 43, 3, pp. 217-218 (August 1983).

37. L. C. Chiu, P. C. Chen and A. Yariv, "Interband Auger Recombination in InGaAsP," IEEE Journ. of Quantum Electronics, QE-18, 6, pp. 938-941 (June 1982).

38. L. C. Chiu and A. Yariv, "Auger Recombination in Quantum-Well InGaAsP heterostructure lasers, IEEE Journ. of Quantum Electronics, QE-18, 10, pp. 1406-1409 (October 1982).

39. A. Mooradian, Phys. Today, 38, 5 (1985).

40. C. H. Henry, IEEE J. Quant. Electron., QE-18, p. 259 (1982).

41. K. Vahala and A. Yariv, "Semiclassical Theory of Laser Noise: Part One," J. Quant. Electron., QE-19, p. 1096 (1983).

42. K. Vahala and A. Yariv, "Semiclassical Theory of Laser Noise: Part Two," J. Quant. Electron., QE-19, p. 1102 (1983).

43. K. Vahala, L. C. Chiu, S. Margalit and A. Yariv, "On the Linewidth Factor α in Semiconductor Injection Lasers," Appl. Phys. Lett., 42, p. 631 (1983).

44. Ch. Harder, K. Vahala and A. Yariv, "Measurement of the Linewidth Enhancement Factor of α of Semiconductor Lasers," Appl. Phys. Lett., 42, p. 328 (1983).

45. K. Vahala, Ch. Harder and A. Yariv, "Observation of Relaxation Resonance Effects in the Field Spectrum of Semiconductor Lasers," Appl. Phys. Lett., 42, p. 211 (1983).

46. S. Piazolla, P. Spano and M. Tamburini, Appl. Phys. Lett., 41, p. 695 (1982).

47. K. Vahala and A. Yariv, "Application of an Electronic Wave-packet Formalism to Local-Operator Equations of Motion for Semiconductor Lasers," Phys. Rev. A, 32, p. 345 (1985).

48. R. Lang, K. Vahala and A. Yariv, "The Effect of Spatially Dependent Temperature and Carrier Fluctuations on Noise in Semiconductor Lasers," IEEE J. Quant. Electron., QE-21, p. 443 (1985).

49. T. G. Hodgkinson, D. W. Smith, R. Wyatt and D. J. Malyon, Br. Telecom. Technol. J., 3, 3 (1985).

50. K. Vahala and A. Yariv, "Detuned Loading in Coupled Cavity Semiconductor Lasers--Effect on Quantum Noise and Dynamics," Appl. Phys. Lett. 45, p. 501 (1984).

51. K. Vahala, J. Paslaski and A. Yariv, "Observation of Modulation Speed Enhancement, Frequency Modulation Suppression and Phase Noise Reduction by Detuned Loading in a Coupled-Cavity Semiconductor Laser," Appl. Phys. Lett., 46, p. 1025 (1985).

52. Y. Arakawa, K. Vahala and A. Yariv, "Quantum Noise and Dynamics in Quantum Well and Quantum Wire Lasers," Appl. Phys. Lett., 45, p. 950 (1984).

MANUSCRIPTS PUBLISHED DURING CONTRACT PERIOD:

J. Salzman, R. Lang, A. Yariv, "Efficiency of Unstable Resonator Semiconductor Lasers," Electronics Letters, vol. 21, no. 18, (August 1985).

C. Lindsey, P. Derry, A. Yariv, "Tailored-Gain Broad-Area Semiconductor Laser With Single-Lobed Diffraction-Limited Far-Field Pattern," Electronics Letters, vol. 21, no. 16, pp. 671-673 (August 1985).

K. Vahala and A. Yariv, "Application of an Electronic Wave-packet Formalism to Local-Operator Equations of Motion for Semiconductor Lasers," Physical Review A, vol. 32, no. 1, pp. 345-356 (July 1985).

J. Salzman, R. Lang and A. Yariv, "Lateral Coupled Cavity Semiconductor Laser," Applied Physics Letters, vol. 47, no. 3, pp. 195-197 (August 1985).

J. Salzman, R. Lang, S. Margalit and A. Yariv, "Tilted-Mirror Semiconductor Lasers," Applied Physics Letters, vol. 47, no. 1, pp. 9-11 (July 1985).

S. H. Izadpanah, J. Paslaski, Z. Rav-Noy, S. Margalit and A. Yariv, "Variable Frequency Picosecond Optical Pulse Generation From Laser Diodes by Electrical Feedback," Appl. Phys Ltrs, vol. 46, no. 11, pp. 1030-1032 (June 1985).

M. Mittelstein, J. Salzman, T. Venkatesan, R. Lang and A. Yariv, "Coherence and Focusing Properties of Unstable Resonator Semiconductor Lasers," Applied Physics Letters, vol. 46, no. 10, pp. 923-925 (May 1985).

J. Salzman, T. Venkatesan, S. Margalit and A. Yariv, "Double Heterostructure Lasers with Facets Formed by a Hybrid Wet and Reactive-Ion Etching Technique," Journal of Applied Physics, vol. 57, no. 8, pp. 2948-2950 (April 1985).

M. B. Yi, L. T. Lu, E. Kapon, Z. Rav-Noy, S. Margalit and A. Yariv, "Cd Diffused Mesa-Substrate Buried Heterostructure InGaAsP/InP Laser," Appl. Phys. Lett., vol. 46, no. 4 (February 1985).

A. Yariv, "The Beginning of Integrated Optoelectronic Circuits," IEEE Transactions on Electron Devices, vol. ED-31, no. 11 (November 1984).

J. Salzman, T. Venkatesan, R. Lang, M. Mittelstein and A. Yariv, "Unstable Resonator Cavity Semiconductor Lasers," Applied Physics Letters, vol. 46, no. 3, pp. 218-220 (February 1985).

E. Kapon, L. T. Lu, Z. Rav-Noy, M. Yi, S. Margalit, A. Yariv, "Phased Arrays of Buried-Ridge InP/InGaAsP Diode Lasers," Appl. Phys. Lett., vol. 46, no. 2, pp. 136-138 (January 1985).

E. Kapon, Z. Rav-Noy, L. T. Lu, M. Yi, S. Margalit and A. Yariv, "Phase-Locking Characteristics of Coupled Ridge-Waveguide InP/InGaAsP Diode Lasers," Applied Physics Letters, vol. 45, no. 11, pp. 1159-1161 (December 1984).

E. Kapon, C. P. Lindsey, J. S. Smith, S. Margalit and A. Yariv, "Inverted-V Chirped Phased Arrays of Gain-Guided GaAs/GaAlAs Diode Lasers," Applied Physics Letters, vol. 45, no. 12, pp. 1257-1259 (December 1984).

J. Katz, E. Kapon, S. Margalit, A. Yariv, "Rate Equations Analysis of Phase-Locked Semiconductor Laser Arrays Under Steady State Conditions," IEEE Journal of Quantum Electronics, vol. QE-20, no. 8, pp.875-879 (August 1984).

J. Katz, E. Kapon, S. Margalit and A. Yariv, "Recent Developments in Monolithic Phase-Locked Semiconductor Laser Arrays," SPIE, vol. 465 (1984).

S. Mukai, C. Lindsey, J. Katz, E. Kapon, Z. Rav-Noy, S. Margalit and A. Yariv, "Fundamental Mode Oscillation of a Buried Ridge Waveguide Laser Array," Applied Physics Letters, vol. 45, no. 8, pp. 834-835 (October 1984).

Y. Arakawa, K. Vahala and A. Yariv, "Quantum Noise and Dynamics in Quantum Well and Quantum Wire Lasers," vol. 45, no. 9, pp. 950-952 (August 1984).

C. P. Lindsey, E. Kapon, J. Katz, S. Margalit and A. Yariv, "Single Contact Tailored Gain Phased Array of Semiconductor Lasers," Applied Physics Letters, vol. 45, no. 7, pp. 722-724 (October 1984).

D. L. Robinson, W. K. Marshall, J. Katz, J. S. Smith, and A. Yariv, "Monolithically Integrated Array of GaAlAs Electroabsorption Modulators," Electronics Letters, vol. 20, no. 17, pp. 678-680 (August 1984).

E. Kapon, J. Katz, S. Margalit and A. Yariv, "Controlled Fundamental Supermode Operation of Phase-Locked Arrays of Gain-Guided Diode Lasers," Applied Physics Letters, vol. 45 no. 6, pp. 600-602 (September 1984).

K. Vahala and A. Yariv, "Detuned Loading in Coupled Cavity Semiconductor Lasers--Effect on Quantum Noise and Dynamics," Applied Physics Letters, vol. 45, no. 5, pp. 501-503 (September 1984).

S. H. Izadpanah, Z. Rav-Noy, S. Mukai, S. Margalit and A. Yariv, "Mutual Phase Locking of a Coupled Laser Diode-Gunn Diode Pair," Applied Physics Letters, vol. 45, no. 6, pp. 609-610 (September 1984).

J. Katz, E. Kapon, C. Lindsey, S. Margalit and A. Yariv, "Coupling Coefficient of Gain-Guided Lasers," Applied Optics, vol. 23, no. 14, pp. 2231-2233 (July 1984).

Z. Rav-Noy, L-T. Lu, E. Kapon, S. Mukai, S. Margalit and A. Yariv, "Vertical Field-Effect Transistors in III-V Semiconductors," Applied Physics Letters, vol. 45, no. 3, pp. 258-260 (August 1984).

E. Kapon, C. Lindsey, J. Katz, S. Margalit and A. Yariv, "Chirped Arrays of Diode Lasers for Supermode Control," Applied Physics Letters, vol. 45, no. 3, pp. 200-202 (August 1984).

Z. Rav-Noy, U. Schreter, S. Mukai, E. Kapon, J. S. Smith, L. C. Chiu, S. Margalit and A. Yariv, "Vertical FET's in GaAs," IEEE Electron Device Letters, vol. EDL-5, no. 7, pp. 228-230 (July 1984).

E. Kapon, J. Katz, A. Yariv, "Supermode Analysis of Phase-Locked Arrays of Semiconductor Lasers," Optics Letters, vol. 9, pp. 125-127 (April 1984).

A. Yariv, "Keynote Address: The Semiconductor Diode Laser: History and Perspective," Proceedings of the International Conference on Lasers'83, pp. 1-6.

J. Katz, E. Kapon, C. Lindsey, S. Margalit, A. Yariv, "Far Field Distributions of Semiconductor Phase-Locked Arrays With Multiple Contacts," Electronics Letters, vol. 19, no. 17, pp. 660-662 (August 1983).

L. C. Chiu, C. Harder, S. Margalit, A. Yariv, "Graded Collector Heterojunction Bipolar Transistor," Applied Physics Letters, vol. 44, no. 1, pp. 105-106 (January 1984).

E. Kapon, C. Lindsey, J. Katz, S. Margalit, A. Yariv, "Coupling Mechanism of Gain-Guided Integrated Semiconductor Laser Arrays," Applied Physics Letters, vol. 44, no. 4, pp. 389-391 (February 1984).

Z. Rav-Noy, C. Harder, U. Shreter, S. Margalit, A. Yariv, "High-Speed Schottky Photodiode on Semi-Insulating GaAs," Electronics Letters, vol. 19, no. 19, pp. 753-754 (September 1983).

E. Kapon, J. Katz, S. Margalit, A. Yariv, "Longitudinal-Mode Control in Integrated Semiconductor Laser Phased-Arrays by Phase Velocity Matching," Applied Physics Letters vol. 44, no. 2, pp. 157-159 (January 1984).

B. Crosignani, A. Yariv, "Degenerate Four-Wave Mixing in the Presence of a Nonuniform Pump Wavefront," Journal of the Optical Society of America A, vol. 1, pp.1034-1039 (October 1984).

L. C. Chiu, K. L. Yu, S. Margalit, T. R. Chen, U. Koren, A. Hasson, A. Yariv, "Field and Hot Carrier Enhanced Leakage in InGaAsP/InP Heterojunctions," IEEE Journal of Quantum Electronics, vol. QE-19, no. 9, pp. 1335-1338 (September 1983).

S. Mukai, E. Kapon, J. Katz, C. Lindsey, Z. Rav-Noy, "Coupled Parallel Waveguide Semiconductor Laser," Applied Physics Letters, vol. 44, no. 5, pp. 478-480 (March 1984).

A. Hasson, L. C. Chiu, T. R. Chen, U, Koren, Z. Rav-Noy, K. L. Yu, S. Margalit and A. Yariv, "Selective Low-Temperature Mass Transport in InGaAsP/InP Lasers," Applied Physics Letters, vol. 43, no. 5, pp. 403-405 (September 1983).

E. Kapon, J. Katz, C. Lindsey, S. Margalit, and A. Yariv, "Control of Mutual Phase Locking of Monolithically Integrated Semiconductor Lasers," Applied Physics Letters, vol. 43, no. 5, pp. 421-423 (September 1983).

J. Katz, E. Kapon, C. Lindsey, S. Margalit, U. Shreter and A. Yariv, "Phase-Locked Semiconductor Laser Array with Separate Contacts," Applied Physics Letters, vol. 43, no. 6, pp. 521-523 (September 1983)

T. R. Chen, B. Chang, L. C. Chiu, K. L. Yu, S. Margalit, and A. Yariv, "Carrier Leakage and Temperature Dependence of InGaAsP Lasers," Applied Physics Letters, vol. 43, no. 3, pp. 217-218 (August 1983).

T. R. Chen, K. L. Yu, B. Chang, A. Hasson, S. Margalit and A. Yariv, "Phase-Locked InGaAsP Laser Array with Diffraction Coupling," Applied Physics Letters, vol. 43, no. 2, pp. 136-137 (July 1983).

J. Katz, S. Margalit, A. Yariv, "Diffraction Coupled Phase-Locked Semiconductor Laser Array," Applied Physics Letters, vol. 42, no. 7, pp. 554-556 (April 1983).

J. Katz, E. Kapon, S. Margalit, A. Yariv, "Recent Developments in Monolithic Phase-Locked Semiconductor Laser," S.P.I.E., vol. 465--Spatial Light Modulators and Applications, pp. 176-180 1984.

K. Vahala, A. Yariv, "Occupation Fluctuation Noise: A Fundamental Source of Linewidth Broadening in Semiconductor Lasers," Applied Physics Letters, vol. 43, no. 2, pp. 140-142 (July 1983).

T. R. Chen, L. C. Chiu, K. L. Yu, U. Koren, A. Hasson, S. Margalit, A. Yariv, "Very Low Threshold InGaAsP Mesa Laser,," IEEE Joural of Quantum Electronics, vol. QE-19, no. 5, pp. 783-785 (May 1983).

J. S. Smith, L. C. Chiu, S. Margalit and A. Yariv, "A New Infrared Detector Using Electron Emission from Multiple Quantum Wells," Journal of Vacuum Science Technology, vl. B1, no. 2, pp. 376-378 (June 1983).

T. R. Chen, S. Margalit, U. Koren, K. L. Yu, L. C. Chiu, A. Hasson, and A. Yariv, "Direct Measurement of the Carrier Leakage in an InGaAsP/InP Laser," Applied Physics Letters, vol. 42, no. 12, pp. 1000-1002 (June 1983).

T. R. Chen, L. C. Chiu, K. L. Yu, U. Koren, A. Hasson, S. Margalit, A. Yariv, "Dependence of To on P-Cladding Layer Doping Level in InGaAsP Lasers," Japanese Journal of Applied Physics, vol. 22, no. 9, pp. L559-L561 (September 1983).

J. Katz, S. Margalit, A. Yariv, "A Proposed New Method for Damping Relaxation Oscillations in Laser Diodes," IEEE Electron Device Letters, vol. EDL-3, no. 11, pp. 333-335 (November 1982).

U. Koren, T. R. Chen, C. Harder, A. Hasson, K. L. Yu, L. C. Chiu, S. Margalit, A. Yariv, "InGaAsP/InP Undercut Mesa Laser with Planar Polyimide Passivation," Applied Physics Letters, vol. 42, no. 5, pp. 403-405 (March 1983).

C. Harder, J. S. Smith, K. Y. Lau, A. Yariv, "Passive Mode Locking of Buried Heterostructure Lasers with Nonuniform Current Injection," Applied Physics Letters, vol. 42, no. 9, pp. 772-774 (May 1983).

U. Koren, Z. Rav-Noy, A. Hasson, T. R. Chen, K. L. Yu, L. C. Chiu, S. Margalit, A. Yariv, "Short Cavity InGaAsP/InP Lasers with Dielectric Mirrors," Applied Physics Letters, vol. 42, no. 10, pp. 848-850 (May 1983).

K. Vahala, L. C. Chiu, S. Margalit, A. Yariv, "On the Linewidth Factor S in Semiconductor Injection Lasers," Applied Physics Letters, vol. 42, no. 8, pp. 631-633 (April 1983).

K. Vahala, A. Yariv, "Semiclassical Theory of Laser Noise: Part Two," IEEE Journal of Quantum Electronics, vol. QE-19, no. 6, pp. 1102-1109 (June 1983).

K. Vahala, A. Yariv, "Semiclassical Theory of Laser Noise: Part One," IEEE Journal of Quantum Electronics, vol. QE-19, no. 6, pp. 1096-1101 (June 1983).

K. Vahala, C. Harder, A. Yariv, "Observation of Relaxation Resonance Effects in the Field Spectrum of Semiconductor Lasers," Applied Physics Letters, vol. 42, no. 3, pp. 211-213 (February 1983).

C. Harder, K. Vahala, A. Yariv, "Measurement of the Linewidth Enhancement Factor of S of Semiconductor Lasers," Applied Physics Letters, vol. 42, no. 4, pp. 328-330 (February 1983).

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A research program in semiconductor lasers and related phenomena resulted in new understanding relating to coherent single lobe laser arrays and to structures displaying near-diffraction-limited output. Using our molecular beam epitaxial reactor, we have demonstrated new unstable resonator geometry of semiconductor lasers which potentially are capable of producing large aperture high power without the need for arrays. Typical powers of $\sim$0.4 Watt were demonstrated in a single mode. Basic theoretical analysis and experiments on noise

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in semiconductor lasers has resulted in a new quantum formulation which takes into account the amplitude to phase coupling. This coupling is characterized by a new dispersive parameter α. Direct measurement of α were performed. Keywords

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